

Characterization of SiC Schottky Diodes at Different Temperatures

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Abstract—The emergence of silicon carbide- (SiC-) based power semiconductor switches, with their superior features compared with silicon- (Si-) based switches, has resulted in substantial improvement in the performance of power electronics converter systems. These systems with SiC power devices have the qualities of being more compact, lighter, and more efficient; thus, they are ideal for high-voltage power electronics applications. In this study, commercial Si pn and SiC Schottky diodes are tested and characterized, their behavioral static and loss models are derived at different temperatures, and they are compared with respect to each other.

Index Terms—Loss model, Schottky diodes, silicon carbide, temperature.

I. INTRODUCTION

PRESENTLY, almost all the power electronics converter systems use silicon- (Si-) based power semiconductor switches. The performance of these switches is approaching the theoretical limits of the Si material. Another material, silicon carbide (SiC), with superior properties compared to Si, is a good candidate to be used in the next generation of power devices, especially for high voltage or high temperature applications. Several papers have compared and contrasted Si-based and SiC-based power electronic devices and have described the relative merits of using wide band gap semiconductors like silicon carbide for high voltage applications [1]–[5].

In the literature, some earlier publications [6]–[12] have shown the applications of SiC Schottky diodes but without any models. In [13], [14], switching loss behavior of experimental SiC diodes has been discussed at different temperatures without mentioning the static characteristics and the modeling equations. In [15], detailed models of SiC diodes have been presented. These would be useful for circuit-level simulations but would take much of the valuable computer time in system level studies. In this study, commercial Si pn and SiC Schottky diodes are tested, characterized and their behavioral static and loss models are derived at different temperatures; they are then compared with respect to each other.

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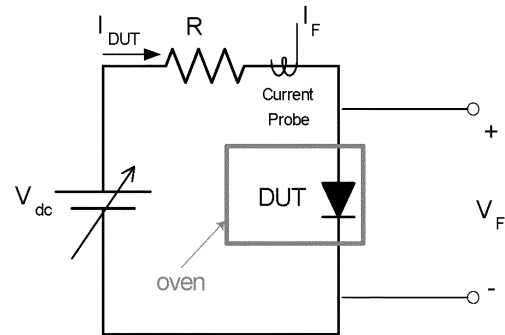


Fig. 1. I – V characterization circuit.

II. DIODE MODELING

SiC Schottky diodes used in this study are rated at 300 V and 10 A and have been obtained directly from Infineon AG [16] in Germany. In the next two subsections, testing, characterization, and loss modeling of Si pn and SiC Schottky diodes will be described and they will be compared with respect to each other. The main reason for comparing pn diodes to Schottky diodes is because SiC Schottky diodes are projected to replace Si pn diodes in the 300–1200 V range.

A. Conduction Losses

The circuit in Fig. 1 is set up with test diodes in a temperature-controlled oven to obtain the I – V characteristics of the diodes at different operating temperatures. The dc voltage supply is varied, and the diode forward voltage and current are measured at different load currents and several temperature values of up to 250 °C (the temperature limit of the oven). The I – V curves obtained as a result of this test for both Si pn and SiC Schottky diodes are given in Fig. 2, in which it can be seen that the forward voltage of the SiC diode is higher than that of the Si diode. This is expected because of SiC's wider bandgap. Another difference between these two diodes is their high-temperature behavior. As the temperature increases, the forward characteristics of the Si diode change severely, while those of the SiC diode stay confined to a narrow region. Note that the pn diode (negative) and the Schottky diode (positive) have different polarity temperature coefficients for on-state resistance; that is why the slope of the curve at higher currents is increasing in the Si diode case and decreasing in the SiC diode case with the temperature increase.

If a line is drawn along the linear high-current portion of the I – V curves extending to the x-axis, the intercept on the x-axis is V_D and the slope of this line is $1/R_D$. The parameters, V_D and R_D , thus obtained, are plotted in Fig. 3. As mentioned previously, because of different temperature coefficients,

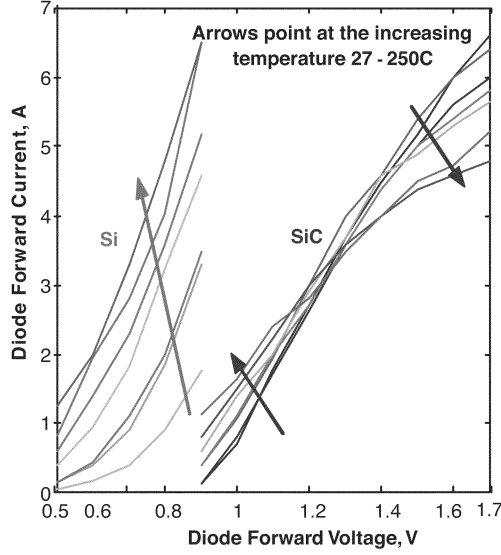


Fig. 2. Experimental I - V characteristics of the Si and SiC diodes in an operating temperature range of 27 °C to 250 °C.

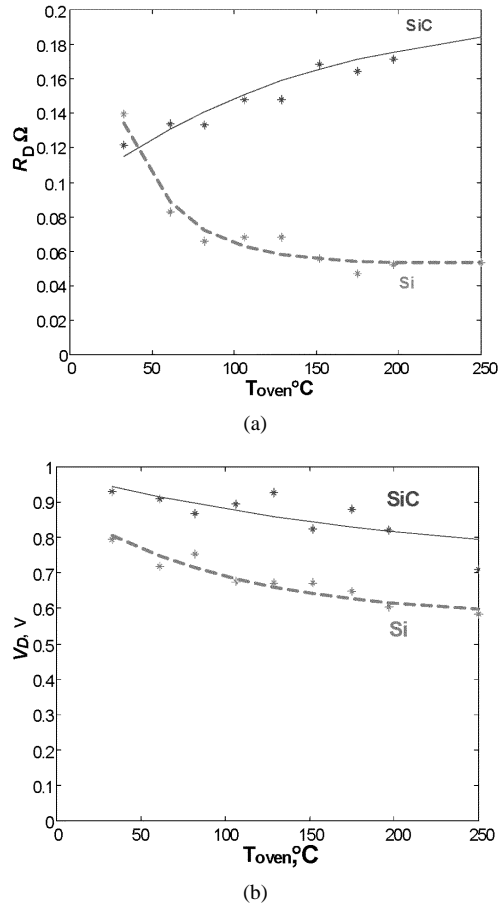


Fig. 3. Variation of (a) R_D and (b) V_D with temperature.

R_D of the Si diode is decreasing and that of the SiC diode is increasing. Only at low temperatures is the SiC on-resistance lower than that of Si. However, Si has a lower voltage drop, which also decreases with temperature. Lower on-resistance and lower voltage drop imply lower conduction losses for the Si diode (for more information, see [17]).

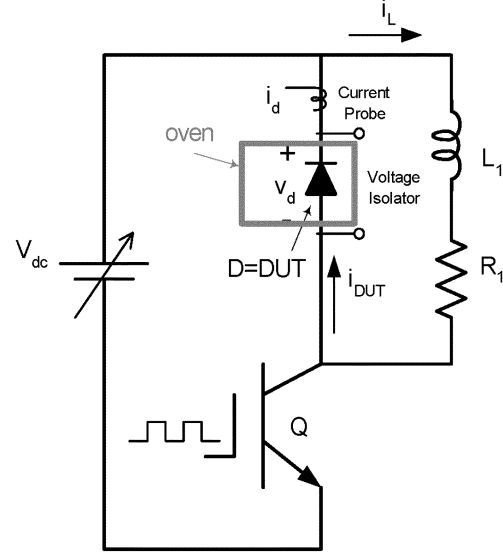


Fig. 4. Reverse recovery loss measurement circuit.

The changes in R_D and V_D are modeled using a curve-fitting method as also plotted in Fig. 3. The equations describing the curves are

$$V_D^{SiC} = 0.2785e^{-0.0046T} + 0.7042 \quad (1)$$

$$R_D^{SiC} = -0.1108e^{-0.0072T} + 0.2023 \quad (2)$$

$$V_D^{Si} = 0.3306e^{-0.0103T} + 0.5724 \quad (3)$$

$$R_D^{Si} = 0.2136e^{-0.0293T} + 0.0529 \quad (4)$$

where T is in °C.

Equations (1)–(4) can be used to derive the diode loss equations in a power converter system. For a three-phase, sinusoidal PWM inverter, the conduction loss for a diode can be simply expressed as [17], [18]

$$P_{cond,D} = I^2 \cdot R_D \cdot \left(\frac{1}{8} - \frac{1}{3\pi} M \cos \phi \right) + I \cdot V_D \cdot \left(\frac{1}{2\pi} - \frac{1}{8} M \cos \phi \right) \quad (5)$$

where M is the modulation index and ϕ is the power factor angle.

B. Switching Losses

The most important part of the diode switching loss is the reverse recovery loss. The rest of the losses are negligible. In this paper, the energy lost during reverse recovery will be calculated experimentally so that the switching losses can be calculated for any switching frequency.

Note that, Schottky diodes, unlike pn diodes, do not have reverse recovery behavior because they do not have minority carriers; however, they still show some reverse recovery effects. The main reason for these effects is the oscillation due to the parasitic device capacitance and the inductances in the circuit. The second reason is the parasitic pn diode formed by the p-rings inserted to decrease the reverse leakage currents and n-type drift region.

For this test, the chopper circuit in Fig. 4 was set up with test diodes in a temperature-controlled oven. The main switch Q is

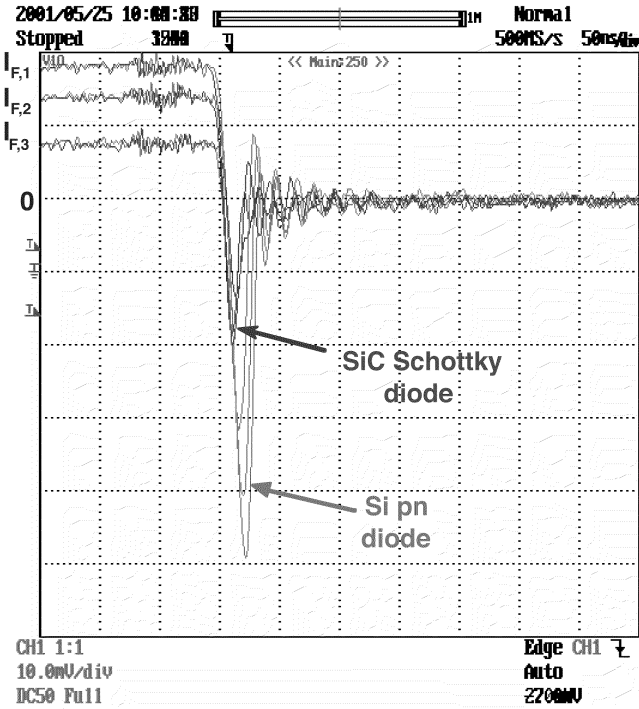


Fig. 5. Typical reverse recovery waveforms of the Si pn and SiC Schottky diode for three different forward currents (2 A/div.).

turned on and off at 1 kHz with a duty ratio of 75%. The typical Si and SiC diode turn-off waveforms are given in Fig. 5 for three different forward currents. These experimental waveforms show that the Si diode switching losses are almost three times more than those of the SiC diode.

The peak reverse recovery current, I_R , and the reverse recovery current-time integral of the diodes are measured at different operating temperatures with varying load currents. The peak reverse recovery current at different temperatures is plotted in Fig. 6 with respect to the forward current. I_R of the Si diode is higher than that of the SiC diode at any operating temperature. As the temperature increases, the difference increases because the I_R of the Si diode increases with temperature, but that of the SiC diode stays constant.

The reverse recovery current-time integral can be used to calculate the reverse recovery losses, and thus the diode switching losses. Assuming the diode sees a constant reverse voltage when it is off and it is switched at constant frequency, then

$$P_{rr} = f_s \cdot V_R \cdot \int_a^b i_d dt. \quad (6)$$

Using the experimentally measured values in (6), reverse recovery losses for a 20 kHz operation with a 300 V reverse voltage are plotted in Fig. 7. As observed in this figure, the SiC Schottky diode switching losses, unlike those of the Si pn diode, do not change much with temperature.

The reverse recovery time-integral current can be approximated linearly as a function of the forward current

$$\int_a^b i_d dt = \alpha \cdot I_F + \beta. \quad (7)$$

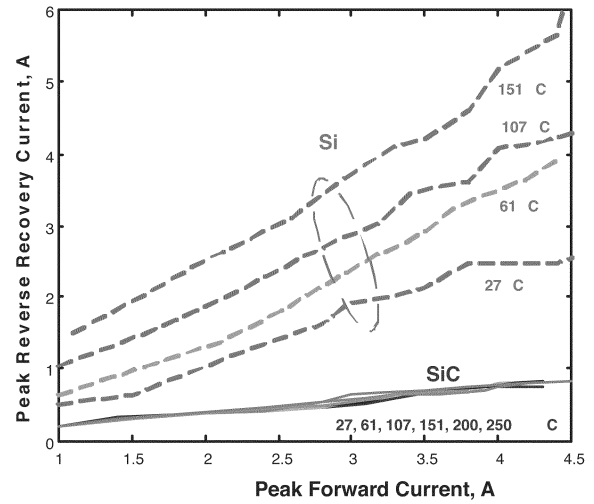


Fig. 6. Peak reverse recovery values with respect to the forward current at different operating temperatures.

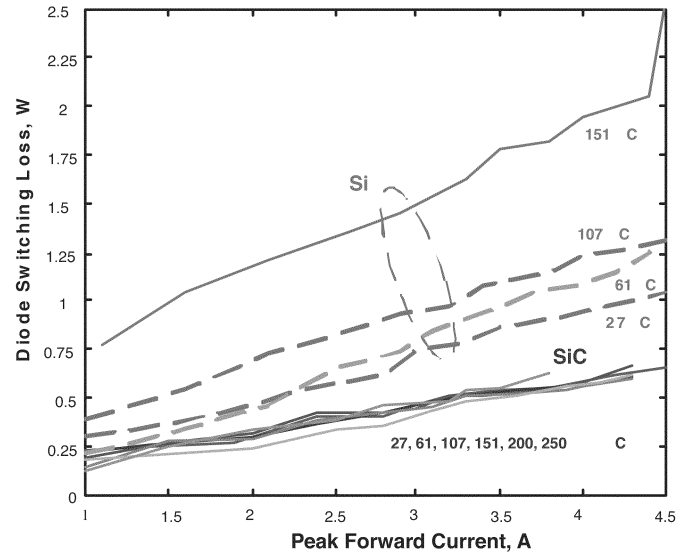


Fig. 7. Diode switching loss of Si and SiC diodes at different operating temperatures.

Then,

$$P_{rr} = f_s \cdot V_R \cdot \int_a^b i_d dt = f_s \cdot V_R \cdot (\alpha \cdot I_F + \beta) \quad (8)$$

where for the SiC Schottky diode $\alpha = 2.167 \times 10^{-8}$ and $\beta = 2.33 \times 10^{-8}$ and for the Si pn diode

$$\alpha = 3.5 \times 10^{-8} + 2.5 \times 10^{-13} \cdot T^{2.31} \quad (9)$$

$$\beta = 1.25 \times 10^{-8} + 2.3 \times 10^{-15} \cdot T^{3.53} \quad (10)$$

and T is in degrees Celsius.

Equations (8)–(10) can be used to calculate the switching losses of Si and SiC diodes in system level models to show the system level benefits of SiC devices [18], [19].

Note that the curves in Figs. 6 and 7 are for up to 150 °C for the Si diode and 250 °C for the SiC diode. The reason for this is that during the tests the Si diode failed when operating at

150 °C and 4.5 A, while the SiC diode survived that temperature and failed at a higher 250 °C and 4 A. When the Si diode failed, the packaging was intact; however, when the SiC diode failed, its package popped open at the corner where the diode was positioned.

III. CONCLUSIONS

The diodes compared in this paper show that SiC diode conduction losses are larger than those of the Si diode, but that the reverse is true for the switching losses. SiC diode switching losses are much less than those of the Si diode, and as the switching frequency and the operating temperature increase, the difference in losses increases even more.

Because the switching and the conduction loss characteristics of the SiC Schottky diode do not change much with temperature, the SiC devices are more reliable. Note that SiC technology is still in its infancy. When this technology matures, controlled switching power devices in the medium-to-high power range will also show these same advantages.

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